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Inductive System Diagrams: An Empirically Based Theory Generation Technique

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Abstract:
Social scientists, over the past sixty years, have developed methodologies to generate theory through an inductive process based on the intensive analysis of a small number of data sources. However, a difficulty associated with these, and most styles of qualitative theory development, is conveying credibility. Inductive System Diagrams combine aspects of Grounded Theory methods and System Dynamics to generate theory with verifiable data, explicit inferences and testable predictions. Grounded theory approaches are used to develop the variables which have a great deal of explanatory power and are intimately tied to the data. The cause and effect relationships among these variables are then shown using causal-loop diagramming techniques from System Dynamics. This combination of grounded theory and causal-loop diagramming allows researchers to generate and communicate empirically based theories.

1. Introduction and Motivation

"Technically a 'qualitative observation' identifies the presence or absence of something, in contrast to 'quantitative observation,' which involves the degree to which some feature is present" (Kirk & Miller 1990; p.9). Participant observers gather data in the daily life of the organization studied (Becker 1969). Forrester (1992; p.57) states the professional literature emphasizes how decisions should be made rather than how they are made and "there is not yet an adequate literature on what constitutes the practice of identifying decision-making policy." In Forrester's view (1992; p. 52), "perceptive observation, searching discussions with persons making the decisions, study of already existing data, and examination of specific examples of decisions and actions all illuminate factors that influence decisions." Gaining the level of insight indicated by Forrester to generate a theory of how decisions are actually made, will, due to the demands placed on the researcher and decision making agents, limit the number and nature of cases which can be studied. These constraints on sample size and selection challenge traditional research validity requirements (Cook & Campbell 1979).

In theory generation research, data collection and analysis are conducted concurrently (Glaser & Strauss 1967, Barton & Lazarsfeld 1969, Miles & Huberman 1984, Schein 1987). "Qualitative research in general and theory generation in particular, is essentially an investigative process, not unlike detective work. Observing one class of events calls for a comparison with a different class. Understanding one relationship reveals several facets which have to be teased out and studied individually. The theory is developed in large part by contrasting, comparing, replicating, cataloguing, and classifying the subject of the study" (Miles & Huberman 1984; p.37). Without joint data collection, coding, and analysis, the subtleties in the area of study, and opportunities to

investigate them, can be lost. As a result, the evolving nature of desired information precludes the establishment of detailed, pre-specified, random sampling plans (Glaser & Strauss 1967, Barton & Lazarsfeld 1969) which violates basic requirements of theory verificaton research (Cook & Campbell 1969, Kidder & Judd 1985). However, the words of C.I. Lewis (1929) may best sum up theory generation sample selection requirements: "Knowledge begins and ends in experience; but it does not end in the experience in which it began."

In the remainder of this paper, Section 2 will outline requirements for assessing the validity of empirically based theory generation research. Section 3 will present Inductive System Diagrams as a methodology for developing reliable and valid empirically based theory. Section 4 describes the results of a small scale reliability test of Inductive System Diagrams. Section 5 discusses limitations and Section 6 outlines potential next steps and conclusions.

2. Theory Generation Research Validity

In verification research to test a hypothesis, the investigator must already know what it is they are going to discover (Kirk & Miller 1990). In theory generation research, by definition, the researcher does not know what they are going to discover. The relatively small sample sizes and lack of reliance on random sampling techniques associated with the theoretical sampling requirements of grounded theory methods generate conflict with many of the traditional tests of validity outlined by Cook and Campbell (1979). As a result, a fundamental issue of theory generation research is how to express the validity of the developed theories.

Glaser and Strauss (1967) discuss the four properties any grounded theory must have for practical application. The theory must fit the substantive area in which it will be used — the concepts and hypotheses supplied by the theory are

closely tied to the data. Second, it must be readily understood by people in the area — it will make sense to the people working in the area. Third, it must be sufficiently general to be applicable in diverse situations — the level of abstraction must be sufficient to make a variety of situations understandable but not so abstract as to be meaningless. Finally, the theory must allow the user partial control over structure and process — the theory must contain sufficient concepts and their plausible interrelations to allow a person to produce and predict change. In short, the theory can be, and is, used by practitioners to guide what they do.

Argyris, et al.. (1985) also propose four criteria for testing the validity of a theory. First is intersubjectively verifiable data — competent members of the scientific community should be able to agree at the level of observation, even if they disagree at the level of theory. The second criterion is explicit inferences — the logic that connects theory and observation should be explicit. Third is the use of disconfirmable propositions — the results of observations must relate to the acceptance or rejection of the theory. Finally is the concept of public testing — the users of a theory test its validity by comparing actual and predicted consequences following a change in their actions based on the research.

From the Clinician's perspective Schein (1987) states that the validity of a theory can be determined by its ability to predict the response to an intervention. The ethnographic view of validity emphasizes the issues of replication and internal consistency (Van Maanen 1983).

Walter Shewhart, the acknowledged developer of statistical process control, may have said it best when he wrote: "there is an important distinction between valid prediction in the sense of a prediction being true and valid knowledge in the sense of a prediction being justifiable upon the basis of available evidence and accepted rules of inference" (Shewhart 1938; p.). Shewhart (1938) points out that it is

possible for predictions to be valid even when the knowledge supporting them is not. Similarly, valid inferences can be made from faulty evidence. Therefore, if theories result in testable predictions, then the validity of theory generation research can be judged on the basis of its evidence, inferences and predictions.

Revisiting the validity criterion outlined above it would appear that Schein is concerned primarily with prediction. Van Maanen's concerns seem related to evidence and inferences. Glaser and Strauss appear to address evidence and inference but not prediction; in addition they are concerned with generalizability and user accessibility. Argyris, et al. appear to address evidence, inference and prediction. These observations are summarized in the table below.

Glaser & Strauss	Argyris, et al..	Van Maanen Schein	Shewhart
Fit	verifiable data	replication	evidence
Understanding	explicit inferences	internal consistency	inferences
	disconfirmable propositions	prediction	prediction
****	public testing		
allows for control	****		
general applicability			

The three concepts: evidence, inferences and predictions, constitute a set of requirements which, if addressed in theory generation research, would allow researchers to observe and distinguish both the validity of the hypotheses (predictions) and the validity of the theory creation process (evidence and inference). An important caveat is drawn from Kuhn's (1962) arguments on how paradigms affect our abilities to interpret the arguments of others, i.e. because we interpret issues from our paradigm not others, it will be difficult for distinct schools of thought to agree on whether any given piece of "knowledge" is valid because the accepted rules of inference are different. However, at a minimum, it should be possible to assess whether the hypothesis or prediction itself is valid.

Inductive System Diagrams, which combine aspects of Grounded Theory methods and System Dynamics, allow researchers to generate theory which meets the criteria of verifiable data, explicit inferences and testable predictions.

3. Inductive System Diagrams

3.1 Grounded Theory

Grounded theory approaches to generating hypotheses are characterized by the use of an exhaustive (and exhausting) data-coding and memo-writing regimen, as well as the use of the constant comparison method of analysis. A grounded theory development process generally consists of the following activities:

1) The researcher starts by coding each incident in his data for as many categories of analysis as possible. While coding an incident, the researcher attempts to compare this incident with all other incidents in the same category.

2) The researcher regularly stops to record in "theoretical memos" his or her thoughts on the developing theory.

3) As the coding continues, the unit of comparative analysis changes from comparison of incident with incident to comparison of incident with the accumulated knowledge of the category.

4) The accumulated knowledge is integrated into a unified whole.

5) The theory is solidified as major modifications become fewer, non-essential categories are pruned, and higher level concepts are abstracted from the detailed categories previously developed from the data (Glaser 1965, Glaser & Strauss 1967, Glaser 1978, Strauss 1987).

Constant Comparison Method

In the constant comparison method, the objective of the sampling process is to allow for comparisons of differences and similarities among the units of analysis. This process of analyzing the similarities and differences produces the dense category development essential to well grounded theory generation. Minimizing differences among comparison groups increases the likelihood that a lot of information is available for developing of the basic properties and conditions of a category. Identifying similar data under comparison conditions of maximum differences identifies the fundamental explanatory variables. To integrate these variables into theory requires investigating the causes, consequences and constraints of these variables also under comparison conditions of maximized differences (Glaser & Strauss 1967; p56-58).

Variable Development

One of the strengths of grounded theory methods is the coding process for category development (Glaser & Strauss 1967, Glaser 1978, Strauss 1987). "The code conceptualizes the underlying pattern of a set of empirical indicators within the data. Coding gets the analyst off the empirical level by fracturing the data, then conceptually grouping it into codes that then become the theory which explains what is happening in the data" (Glaser 1978; p.55). The process begins with "open-coding", a line by line analysis of the data which is diametrically opposite to the process of coding with preconceived codes. In open-coding the analyst attempts to code the data in as many different ways as possible. The analyst constantly looks for the "main theme", for what appears to be the main concern of or problem for the people in the setting (Strauss 1987; p.35). As the analyst's awareness of the central problem(s) emerges, they alternate open coding with very directed "axial coding". Axial coding consists of analysis done

around one category at a time. As core variables begin to emerge, the analyst employs "selective coding" to focus coding to only those variables that relate to core variables in sufficiently significant ways to be used in parsimonious theory. In all 10 to 15 codes are typically enough for a monograph on a parsimonious substantive theory (Strauss 1987; p.32).

Open Coding

By definition in theory generation research, the essential variables are not known; open coding is the start of the variable development process. During open coding each sentence is explored for as many possible concepts as possible. When coding the concept, it is assigned a variable name which is closely linked to the supporting data. Questions related to the occurrence of the concept are generated. These generative questions build sensitivity for future use in making comparisons when the next occurrence of the concept is encountered (Glaser 1978, Strauss 1987). An example, from my field notes is provided below:

> *"This was a decision node in the conception of the product which was not made by systematic analysis." - R&D manager*
>
> <u>Decision node</u>. What is a decision node? How many are there? What are the necessary conditions for an event to be considered a decision node? Who initiates the decision? Who ratifies the decision? Who monitors them?
>
> <u>Conception</u>. When is a product conceived? What is the gestation period like? I can think of lots of analogies here, prenatal care, miscarriages, etc. ...
>
> <u>Systematic Analysis</u>. What constitutes systematic? unsystematic? When does one favor one over the other? Assuming systematic is preferred; how does one get away with unsystematic analysis?

The open coding process generates a large number of variables quickly. Therefore it is necessary to reduce codes in use. The reduction occurs through a process of abstraction (Hayakawa 1990). In abstraction, variables which convey similar concepts are grouped together and a variable name, which captures the essence of the common concept, is selected to be used in all references to this concept. In some cases, one code in the grouping represents the best label for the concept and it can be used for the variable name. In other cases, it is necessary to create a variable name which captures the common concept. In the example below, tradeoff analysis was selected as the variable name which best captured the common concept in all four codes.

tradeoff analysis
- design constraint tradeoff
- performance comparisons
- conscious dimension sacrifice
- tradeoff equation

Similarly, tradeoff analysis can be subsequently grouped with other variables, e.g. systematic analysis, which relate to a common concept but at a higher level of abstraction.

By investigating events under similar conditions, those concepts which are common in different settings represent the initial pool of potential explanatory variables. (It is highly probable that the final set of variables could be substantially different than the initial set.) Axial coding is used to develop better insight into these variables.

Axial coding

Axial coding represents an attempt to identify he causes, consequences and constraints of a variable under investigation. It is designed to build

substantial knowledge about the selected variable and other variables it relates to (Glaser 1978, Strauss 1987). In studies where both participant observations and interviews are conducted, it can be very productive to conduct a "Causes, Consequences and Constraints" structured interview with participants as soon as possible after observation of the concept of interest. Reviewing existing field notes for evidence of causes, consequences and constraints can also be productive as the following example shows:

> *"Going back and doing the correlation effort yielded the same numbers and is documented. This gives us triple verification of what we are doing. So I'm willing to sign." - design engineer*
>
> <u>Systematic Analysis</u> **causes** <u>Traceability</u> **causes** <u>Confidence</u>

Selective Coding

When a variable begins to stand out as being the core category, as having extra-ordinary explanatory power, it is selected for focused coding. Coding activities are focused exclusively on the selected variable and the other variables with which it has significant relationships. All available data should be considered for review in selective coding (Glaser 1978, Strauss 1987). In this study, KJ diagrams, which structure detailed language (vs. numerical) data into more general conclusions using semantic and abstraction guidelines was used for selective coding (Kawakita 1991, Shiba et al. 1991a).

Iteration

Cycling back and forth between open, axial and selective coding occurs regularly early in the investigation and gradually decreases as the research progresses (Glaser & Strauss 1967, Strauss 1987). For example, at any time

during this process insight regarding the variables or related inferences may occur. When this happens, immediately stop and write a "theoretical memo" before continuing or at a minimum make an appropriate annotation in the field notes as shown below (Glaser 1965, Glaser & Strauss 1967, Glaser 1978, Strauss 1987).

> *"It is becoming increasingly important because this process is taking a long time, not just a long elapsed time because it is not calendar time, but in terms of people time it is extensive" - marketing manager*
>
> Systematic Analysis **causes** Labor Requirements.
> **Memo:** Labor Availability **constrains** Systematic Analysis

The insight (**captured in writing first**) can trigger a change in coding strategy. In the example above, the data show evidence that Systematic Analysis causes Labor Requirements. A logical inference, not supported by the evidence, is that Labor Availability could constrain Systematic Analysis. Accordingly, additional theoretical sampling and/or more open coding connected to the concept of labor could follow from this insight. In another example, an integrating diagram can be developed on the basis of axial coding. Analysis of preliminary diagrams can (often) identify inferences regarding variable relationships which are not supported by available evidence. This can trigger additional theoretical sampling, open coding and/or axial coding as required to explore the proposed relationship.

3.2 System Dynamics

Forrester (1968; p.1-2) argues that a "structure (or theory) is essential if we are to effectively interrelate and interpret our observations in any field of knowledge." A hierarchical framework for identifying the

structure of a system has been identified and developed in the system dynamics field (see for example: Forrester 1968, Goodman 1974, Randers 1980, Richardson and Pugh 1981). These principles of system dynamics can be applied to decision processes to develop their underlying structure (Forrester 1968, Goodman 1974, Randers 1980, Sterman 1989).

At their highest level, systems can be described as being open-loop or closed-loop (Forrester 1968). Forrester identifies open-loop systems as being characterized by current performance which is not influenced by past behavior; open-loop systems do not observe, and therefore react, to their own actions. Closed-loop systems, on the other hand, are characterized by the feedback from past performance influencing current actions. Decision processes are closed-loop systems as they are imbedded in a feedback loop; the decision, based on the available information of the state or condition of the system, controls an action influencing the system condition, which generates new information, which is used to modify the next decision (Forrester 1968; p.4-4).

Interconnecting feedback loops are the basic structural elements in systems which generate dynamic behavior (Forrester 1968, Goodman 1974). "Feedback loops are a closed path connecting in sequence a decision that controls action, the level of the system, and information about the level (or condition) of the system, the latter returning to the decision-making point" (Forrester 1968; p.1-7). However, at a lower level of hierarchy, feedback loops contain a substructure composed of two types of variables — levels and rates (Forrester 1968). The level (or state) variables describe the condition of the system at any particular time while the rate variables tell how fast the levels are changing (Forrester 1968).

To illustrate these points, consider the decision process of filling a glass from a beer tap. When we are thirsty and the glass is empty, the decision is to open the tap fully. As the level of beer in the glass approaches the top, we decide to gradually close down the tap, reducing the rate at which beer enters the glass so that the tap is closed when the glass is full and (hopefully) no beer is wasted.

Causal-loop Diagrams

Causal-loop diagrams identify the principal feedback loops in a system without distinguishing between the nature, i.e. level or rate, of the interconnecting variables (Goodman 1974). Goodman (1974) outlines the steps of developing a causal-loop diagram as follows:

1. establish the pairwise relationships of relevant variables;
2. ascertain the polarity of the causal pairs;
3. fit together the causal pairs into closed loops; and
4. test for loop polarity.

Through this process, the causal-loop diagram allows the analyst to integrate the variables they have developed, explicitly state the inferences they are making and clearly communicate their hypotheses regarding the dynamics associated with the structural relationships of the system.

Pairwise variable relationships are diagrammed with directed arcs. Arcs are used to connect the factors which influence each other; the arrow indicating the direction of influence. Each arc is annotated with an indication of the causal change (polarity) between the two factors.[1] An "S" indicates that the two factors move in the same direction, i.e., all other

---

[1]Goodman (1974) uses '+' and '-' to indicate positive and negative polarity. Senge (1990) and Kim (1992) advocate the use of 'S' and 'O'.

things being equal, as one variable increases the other variable also increases. An "O" indicates that variables move in opposite directions, i.e., all other things being equal, as one factor increases the other factor decreases. These pairwise arcs can then be connected to form feedback loops.

There are two basic types of feedback loops, reinforcing (positive) and balancing (negative) feedback loops which are used to explain the dynamics of complex situations (Forrester 1968, Goodman 1974, Randers 1980). Reinforcing loops promote movement, either growth or decay, by compounding the change in one direction. Balancing loops resist change in one direction and try to bring a system back to a specified goal or equilibrium state. These two simple structures can be combined in an large variety of ways into casual loop diagrams which can be used describe complex systems.

3.3 ISD Step by Step Methodology

The development of Inductive System Diagrams starts with developing, through a verifiable process, the central variables using grounded theory methods and then mapping the explicit inferences drawn from the data analysis through causal loop diagrams. The diagrams are then validated for internal and external consistency.

Step 1: Selecting a Variable

The focus of the investigation is established by identifying significant (core) variables (categories) and their symptoms. The initial selection of a variable is decided by its apparent explanatory ability or central importance in the events being studied. (This implies that considerable open coding and comparative analysis has been conducted

by the researcher.) This can be done through axial coding – the process of specifying the varieties of causes, conditions and consequences associated with the appearance of phenomenon referenced by the variable (Strauss 1987;64).

Step 2: Identifying Causes and Consequences

After a significant variable is identified, the next step is to identify other variables closely related to it. The data are analyzed to identify key factors which appear to drive or be driven by the selected variable. This can be accomplished by selective coding, wherein all other subordinate variables and their dimensions become systematically linked to the selected variable. (Strauss 1987)

Step 3: Describe Factor Relationships

After key factors associated with a variable have been identified, their interactions are diagrammed as causal-loop diagrams. The pairwise directed arcs developed during axial and selective coding are integrated into a closed system. There are usually many variables to explore and it doesn't matter which one is selected first assuming all will be investigated.

Step 4: Check Diagram Consistency

The diagrams should be compared to the collected data to ensure they are grounded in the available facts. Often early diagrams contain links which are not supported by the presented evidence. If upon review, the researcher is confident the loop reflects the system dynamics, additional theoretical sampling or coding is necessary to ensure the theory remains "grounded" in the available data. Additionally, the diagrams should be investigated for "leaps of logic", i.e.. can the diagram describe the patterns of events without explanation. Finally, the diagram is reviewed to ensure factor labels are at the same level of abstraction

(Hayakawa 1990). For example, "*Design Constraint Tradeoff*" and "*Performance Comparison*" would be at the same level of abstraction while the abstracted category, "*Systematic Analysis*" would be at a higher level of abstraction.

Step 5: Integrating Causal-loop Diagrams into an Inductive System Diagram

After all significant variables have been diagrammed, the individual causal-loop diagrams are combined to articulate the underlying structure or theory. A central theme is developed using a clearly dominant (core) variable or by linking variables which are common to multiple causal-loop diagrams. Remaining causal-loop diagrams are incorporated into the central theme. Variables may be combined and re-labeled at a higher level of abstraction (Hayakawa 1990). Additionally, low impact loops are eliminated to simplify the diagram. This integrated ISD is validated for logic flow, abstraction levels, consistency with the data and participants in the area of investigation.

3.4 Product Development Study Example:

An example of the use of ISD in the development of a substantive theory for product development activities follows. The specific coding and analysis examples come from teams using the Concept Engineering method (Burchill et al. 1992). All field notes were exhaustively coded and analyzed (an average of three hours of off-site effort for every hour of recorded notes) by the author and/or a research assistant. Additionally, much of the coding and analysis was reviewed by colleagues in a Field Research Methods Seminar.

One team went from kick-off to product requirement determination in less than two months and on to final product concept selection in only two more months – considerably faster than historical performance. As a result, Development Time was selected for focused investigation (theoretical sampling/axial coding). Examples of relevant quotes from field notes (*italics)* are provided to illustrate the ISD process.

"(On the previous project) This process would have provided a clearer vision[1], a straighter path to the end result[2]. I see the process saving time[3] by eliminating missteps[4]." - Engineering Development Manager

Coding this statement for variable development might create categories for: 1) Design Vision Clarity, 2) Straighter Path, 3) Development Time, and 4) Missteps. Straighter Path and Missteps are conceptually similar and at a higher level of abstraction could both be dimensions of the category Misdirected Effort. These variables can be diagrammed as follows:

$$\text{Design Vision Clarity} \xrightarrow[\text{O}]{} \text{Misdirected Effort} \xrightarrow[\text{S}]{} \text{Development Time}$$

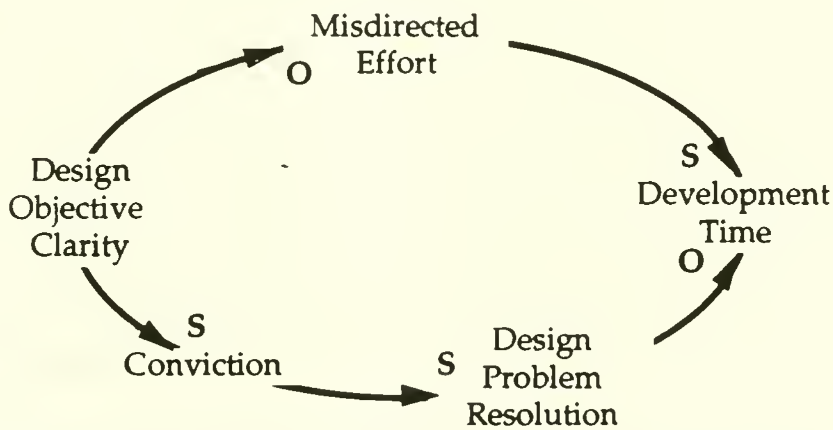
This diagram indicates that as Design Vision Clarity increases Misdirected Effort decreases causing Development Time to also decrease.

The constant comparison method employed in a Grounded Theory approach requires that events be compared to other incidents in the same category. Accordingly, the following incident, from the same team, which relates to Development Time was compared to the instance above.

"Someone that has buy-in[1] understands the how and why and can explain to other people horizontally or vertically[2]. Along with buy-in is a belief or passion[3]. I think that where there is passion there is ownership and those two combined[4]; when they

exist in the same group of people and the team encounters problems they don't last[5]*. The team fixes it and moves on*[6]*."* *- Marketing Product Manager*

Coding this statement for variable development might create categories for: 1) Buy-In, 2) Design Objective Understanding, 3) Passion, 4) Ownership, 5) Design Problem Resolution and 6) Development Progress. To simplify coding, Buy-In, Passion, and Ownership can be combined into an abstracted category Conviction. Additionally, Design Objective Understanding is conceptually similar to the variable Design Vision Clarity in the diagram above and is abstracted into the variable Design Objective Clarity. Development Progress is conceptually similar to the variable Development Time; Development Time will continue to be used as it is less ambiguous then Development Progress. The resulting diagram, integrated with the previous diagram, is shown below:



This diagram adds the conditions that Development Time decreases as Design Problem Resolution increases which in turn is driven by Conviction through Design Objective Clarity. The integrated diagram enhances the ability to compare future instances of Development Time

with the accumulated knowledge by clearly and concisely displaying the current state of accumulated evidence and inferences.

In comparing instances of Development Time from a second team at another company, using the Concept Engineering approach, an important difference was identified. This difference is exemplified by the following quotes:

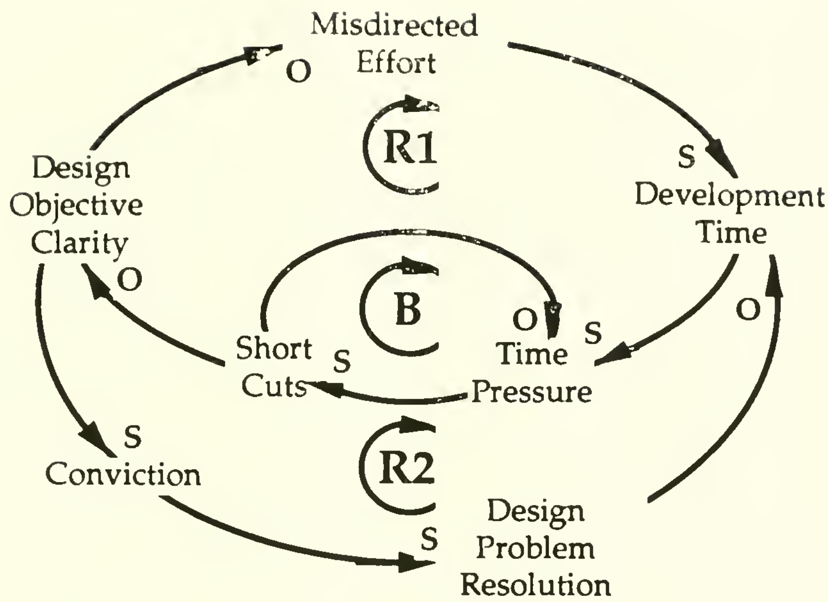
"Also, since we spent a lot of time with the requirement labels yesterday, perhaps we could shortcut a bit on the time without discussion and talk a little sooner." Process Facilitator

"We should generate (requirement metrics) in pairs, then bring the result to a vote. Why not skip the voting step in pairs and vote as a group." Team Leader

From these quotes a new category, Short-Cuts, can be derived. The second team, as a result of several disruptions in their project, planned to complete seven (of fifteen) steps of the Concept Engineering process in one week. Prior efforts, including the first team addressed above, allocated two to three weeks for these same activities. This caused the second team significant, self-imposed, time pressure. Time Pressure was also identified as a relevant variable relating to Development Time. A possible consequence of taking Short-Cuts can best be seen in one of the final comments during the second teams reflection period late Friday afternoon.

"Surprises me, that after all the discussion this week, some people don't know what others are talking about. I should say everyone doesn't know what the others are talking about." Development Engineer

Adding the new categories, Short-Cuts and Time Pressure, to the diagram of accumulated knowledge above, results in the following diagram:



This causal-loop diagram shows two reinforcing loops (R1 and R2) and one balancing loop (B). The reinforcing loops imply that increases in Design Objective Clarity can decrease Development Time and subsequently Time Pressure as a result of less Misdirected Effort and/or as a result of increased Conviction and Design Problem Resolution. The reduction in Time Pressure leads to decreased Short Cuts which increases Design Objective Clarity. The balancing loop implies that as Time Pressure increases Short Cuts also increase, thereby decreasing Time Pressure. However, Short Cuts also decrease Design Objective Clarity causing an increase in Misdirected Effort and a decrease in Conviction. This diagram can be continually validated as additional instances of Development Time come to light; new variables will be added or relationships modified as dictated by the data. Eventually, modifications become fewer and a theory about Development Time, grounded in the data, can be clearly and concisely stated.

4. Inductive System Diagram Reliability Assessment

In the fall of 1992, seven Sloan School graduate students were presented with the Inductive System Diagram instructions, with the example presented above, and extracts of actual field notes. The students ranged from Ph.D. candidates in System Dynamics to M.S. candidates with no prior exposure to System Dynamics. Each student independently prepared an Inductive System Diagram. In addition to providing final diagrams, many of the students also provided annotated transcripts, preliminary diagrams and the amount of time spent on the exercise. (Many of the individuals who indicated more time developed diagrams with fewer variables. I conclude from this, that some participants put more effort into the abstraction and simplification procedure described in step 5 of the Inductive System Diagram process. Therefore, a diagram with fewer variables and relationships may reflect a higher level of synthesis.)

Each diagram was quickly reviewed for conformance with basic system dynamic modeling requirements. One diagram was rejected from further consideration as the author (someone with no system dynamics exposure) duplicated the same variable in multiple loops rather than connecting the loops through a single expression of the variable. The remaining six diagrams were reviewed to assess: the degree to which the diagrams reflect similar variables, the degree to which variables are connected in similar sequence; and the degree to which the overall structure is similar.

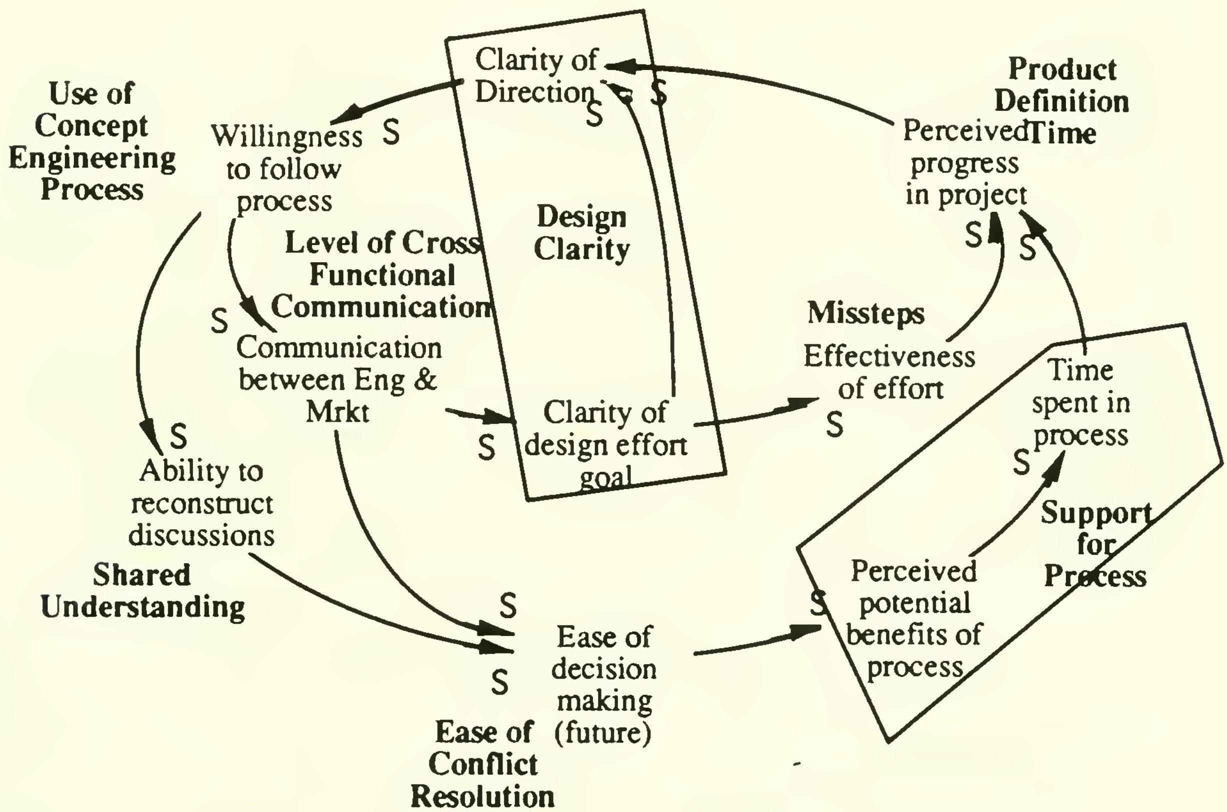
Variable Comparison

To assess the degree to which the diagrams reflected similar variables, each variable was written on a separate slip of paper. Those variables which expressed a similar concept were grouped together. If a grouping contained multiple variable names from the same diagram, the original diagram was reviewed to ensure consolidation of variables was consistent with the original drawing. After

ensuring consistency, the group label was selected as the best exemplar of the concept in the grouping. Variables from each diagram which were not initially placed in a group were then reviewed to see if they could be added to an existing group, without changing diagram structure, to simplify analysis.

Directed Arc Comparison

To assess the degree to which the diagrams reflected similar pairwise associations , each diagram was first redrawn annotating which variables in the original diagram would be consolidated under the exemplar **(bold)** identified during grouping in lieu of the original variable labels. Each diagram was subsequently redrawn using only the common variable names. In redrawing the original diagram with new variable names the sign of the arc connecting two variables may need to be changed.



Example of annotated original diagram
(exemplars in **bold** and consolidated variables in boxes)

Using the redrawn diagrams, with common variable names, each pairwise directed arc connecting two variables was reviewed and the relationship annotated. A two digit code was utilized for audit purposes; the first digit represents the directional relationship and the second digit represents the source diagram number.

From/To	Product Definitio n Time	Cross Function Commin.	Design Clarity	Use of C. E.	Support for Process	Missteps	Ease of Conflict Resolution	Shared Under-standing
Product Definition Time				O2	O1,O3, O4,O6			
Cross Functional Commun.	O5		S1,S2,S3, S4,S6				S2,S3	S1,S6
Design Clarity	O5				S1	O2,O3, O4,O6	S1	S3
Use of Concept Engineer.	O4,O5	S1,S2,S3, S4,S5,S6	S3,S5					S2,S3
Support For Process	S2			S1,S3,S4, S6				
Missteps	S1,S2,S3, S4				O6			
Ease of Conflict Resolution	O1,O3, O6				S1,S2			
Shared Under-standing			S3			O1,O3	S1,S2,S6	

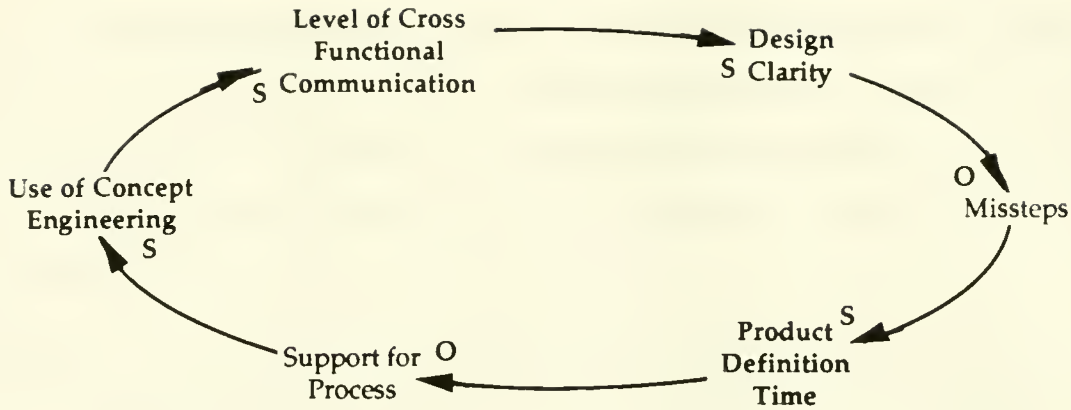
Variable Relationship Matrix

Reliability Assessment Results

A review of the relationship matrix indicated all six diagrams reference the following variables: Product Definition Time, Level of Cross Functional Communication, Design Clarity, and Use of Concept

Engineering. Additionally, all diagrams except diagram 5 also referenced the variables Support for Process and Missteps. Four diagrams also referenced the variables Ease of Conflict Resolution and Shared Understanding. Unfortunately, due to the varying amounts of time spent in developing the diagrams and the differences in modeling experience, I am unable to conclude if the differences in variable inclusion represent failures on the part of the authors to identify the concepts or are the result of more effort at abstraction and simplification. Additionally, a review of the relationship matrix indicates that all variables which were connected by more than one author showed a consistent relationship.

Stepping back from the detailed level of analysis to review the basic structures identified by the authors also shows a high degree of consistency. All six authors show a direct relationship from Use of Concept Engineering to Level of Cross Functional Communication. Five of the six authors show a direct relationship from Level of Cross Functional Communication to Design Clarity and the sixth author shows an inverse relationship to Product Definition Time. Furthermore, four of the remaining five authors map a inverse relationship from Design Clarity to Product Definition Time usually via the intervening variable Missteps. All five authors who show a relationship from Product Definition Time indicate it has an inverse relationship either directly to the Use of Concept Engineering (1 diagram) or indirectly through the variable Support for Process (4 diagrams). In summary, all participants in the study identified the same basic structure.



Common Structure identified by study participants

The results of this preliminary assessment of Inductive System Diagrams indicates that they appear to be reliable with respect to variable identification and integration. However, a more complete test, involving more subjects and evaluators is required before a more definitive statement of reliability can be made.

5. Causal-loop Diagram Limitations

Causal-loop diagrams do not show the level and rate substructure of the system (Goodman 1974, Morecroft 1982, Richardson 1986). In cases involving rate-to-level pairwise directed arcs, the traditional definitions of positive and negative polarity fail because accumulation effects are lost (Richardson 1986). In the filling of the beer glass example used previously in this paper, the link from the rate of beer flow to the level of beer in the glass fails the traditional definition: here a decrease in the rate of flow from the tap will not produce a decrease in the level of beer in the glass (Richardson 1986; p.160). As a result, accurate prediction of system behavior is difficult using only causal-loop diagrams and more detailed

flow diagrams are required before developing simulation models (Goodman 1974, Morecroft 1982, Richardson 1986).

On the other hand, Wolstenholme (1982; p.547) makes a clear distinction between the system description (qualitative) analysis aspects of system dynamics and the simulation modeling (quantitative) techniques and states: "a good system diagram can formalize and communicate a modeler's mental image and hence understanding of a given situation in a way that the written language cannot." Coyle (1983; p.885) states that the difficult part of the operations research discipline is to clearly describe the interrelationships of the system under investigation and that system diagrams require "not much more than patience and persistence to apply ... in reaching a good first approximation to an adequate breadth of view in considering a complex problem." Goodman (1974) concludes that while causal-loop diagrams are insufficient for constructing simulation models they are useful for model conceptualization by organizing principal components and feedback loops.

6. Next Steps and Concluding Remarks

Two research themes could be pursued directly from the initial work on Inductive System Diagrams. First, a more extensive reliability assessment can be conducted and second, research related to enhancing the power of the diagrams should be pursued.

The reliability assessment of Inductive System Diagrams needs to be conducted on a larger sample of testers, some of whom are experienced qualitative researchers. Additionally, the assessment of the diagrams should be conducted by a panel of trained evaluators rather than a single person to increase

result reliability. Finally, given larger sample sizes statistical analysis of the results can be conducted.

The rate-to-level limitations of causal-loop diagrams has been addressed by several systems dynamists through the use of flow diagrams (Forrester 1971, Goodman 1974, Richardson 1981) and Policy Structure diagrams (Morecroft 1982). Prior attempts at representing this additional structural detail unfortunately make the schematic much more difficult to comprehend by the uninitiated. However, it should be possible for the analyst to employ these structural insights in the development and description of their models even if the detail is absent from the presentation schematics.

Additionally, Inductive System Diagrams can be extended by incorporating reference mode analysis into the development process. Reference modes clearly specify the dynamic behavior of interest in the system under investigation (Randers 1980, Richardson and Pugh 1981). Usually reference modes are based on actual historical data but they can also be created from expert assessments (Randers 1980, Richardson and Pugh 1981). Reference modes can be described either graphically or verbally but they must indicate the appropriate time dimensions of the variables described (Randers 1980, Richardson and Pugh 1981). Reference modes can help identify which variables should appear in the model (Randers 1980). Therefore, reference mode analysis could assist not only in the development of variables through theoretical sampling and coding but also in the elimination of variables during diagram integration.

In conclusion, Inductive System Diagrams have been introduced as a diagram-based method for systematic field-based hypothesis development and integration. Inductive System Diagrams build on the strengths of accepted coding practices for variable development. They can

be used to integrate variable relationships and are easily modifiable as additional information becomes available. As a result, they facilitate the ability of researchers to use the constant comparative method of analysis, an accepted approach for theory generation. The Inductive System Diagram method was found to have reliability in a small scale experiment involving experienced and novice dynamic model builders. Additionally, they allow for theory validity testing against the criteria of: verifiable data, explicit inferences and disconfirmable predictions.

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